STRESS DISTRIBUTION IN SPREAD FOOTING FOUNDATIONS - NUMERICAL ANALYSIS

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Abstract. *In this paper stress distribution in different shapes of spread footing has been discussed and an optimization of footing dimensions has been proposed. For the analysis purposes comparison of stress distribution has been performed for six different shapes of spread footing. Spread footings has been divided into two groups, where the first contained foundations with rectangular base and in the second one circular base has been considered, respectively. In both groups three different shapes of spread footing have been analysed – prismatic/cylindrical, prism with sloped edges/cut-off cone and stepped footing. For each spread footing in the centre of their top surface a small part of column has been modelled. Presented in this paper comparative analysis has been limited only to the pure axial loading subjected to the top surface of columns. In order to perform numerical analyses SolidWorks Finite Element Method (FEM) based software has been chosen. Through the analysis it is shown that the best stress distribution for the further weight and shape optimization is obtained in sloped prism and cut-off cone. After the optimization process of the spread footing dimensions one obtained a reduction of approximately 90% of total weight, with acceptable stress value increase.*

Keywords

Stress distribution, spread footing, FEM.

1. Introduction

Foundations are basic part of construction, which transfer the loads from the construction or machines directly onto the ground. Foundations are usually made of concrete, reinforced concrete, rarely from bricks or wood (lightweight constructions). The history of first intentionally utilized foundations reaches times far before the Christ was born – the Mesolithic époque around twelve thousands years B.C. It is known that people built their houses on shallow lakes with the use of wooden piles in order to keep safe from wild animals. Further development of foundations took place in ancient Egypt and in ancient Greece. In Egypt pyramids were settled onto large stones consequently transferring construction weight onto the bedrock. With the invention of concrete in ancient Rome, foundations were much easier to cast, which in consequence contributed to great foundations development. Wide overview of foundations history may be found in [1].

Today, after years of great foundations development the most often utilized are reinforced concrete foundations, where concrete is used as a filler to the steel rebars cage. Concrete transfers compressive forces, whereas steel rebars cage provide transfer tensile forces. In example column located in the centre point of large area foundation results in bending momentum occurring on bottom base surface. According to that, steel rebars are embedded in the concrete mix to provide tensile forces transfer – concrete is a brittle material with a very low tensile load bearing capacity.

Recently utilized foundations may be divided into three groups – shallow, deep and monopile foundations. In the shallow foundation group which are embedded into the ground by around one meter, following footings can be specified: continuous footings, spread footings, slab-on-grade foundations. Deep foundations are used when top surface of soil has low bearing capacity, thus foundations have to reach lower surfaces of ground with appropriate load capacity. For this group one can be counted: impact driven piles, drilled shafts, caissons, helical piles, geo-piers and earth stabilized columns. Monopiles are single, large-diameter foundations embedded to the ground to provide support for large constructions and all its load combinations.

For recently utilized foundations there are few requirements that must be fulfilled:

- Minimal and even subsidence;
- Appropriate depth of settlement;
- Ease of utilization and as small as possible costs;
- Protection from ground humidity.

Moreover, according to the European standards with national appendix [2], [3] foundations should also provide sufficient construction stiffness, should be resistant to the control perimeter punching under the force transferred from column, compressive pressure cannot exceed the ground load bearing capacity, and transferred forces should not result in spread footing pull-off in the range greater than one fourth of considered footing dimension.

Presented calculations of spread footings by the European standards [2], [3] and by engineering help books [4], [5], [6], [7] concerns only small variety of foundations shapes. Owing to that, foundations are designed with greater dimensions than it results from current forces distribution. Of course greater dimensions provide extra safety in spite of unexpected loads, however from economical and engineering point of view, potential of spread footing is not fully utilized. Hence, utilization of FEM software is highly appreciated.

In literature there is also a small number of articles concerning spread footing shape optimization. Authors rather concern on actual loading cases than on footing shapes itself. Bearing capacity of basic shape shallow foundations was widely discussed by Vesic [8]. The differences between currently being in force Eurocode [2] to the Polish national standard [9] in designing of foundations were the subject of interest by Nepelski [10], who stated that the calculations performed on the basis of Eurocode gives higher load bearing capacity results of cohesive and non-cohesive ground under the shallow foundation. In both ground types the differences are higher, the greater ground parameters are being analysed. Bearing capacity of foundations located on slopes with various soil parameters were discussed in [11], [12], [13] and numerical analyses concerning foundations failure mechanism were presented in [14], [15]. Design of footings on seismic exposed areas is a bit different to the basic foundations. Problems of such designs were discussed by Pecker and Pender [16] and Kumar with Mohan Rao [17].

In this paper comparative numerical analysis of stress distribution for six different shapes of spread footing foundations subjected to pure axial loading was performed. Due to the lack number of research concerning foundation shape optimization, on the basis of obtained stress distribution it became possible to make small optimization of spread footing dimensions in order to meet appropriate safety requirements. In consequence casting time and costs could be lowered. For mentioned analysis and optimization, SolidWorks FEM based software was used.

2. Model shapes and assumptions

For the comparative numerical analysis of stress distribution, six different shapes of spread footing were chosen. Models of spread footing can be divided into two groups, where in the first group spread footings with rectangular base shape were analysed and in the second group circular base footings were taken into considerations. In both groups three different shapes in foundations height direction were adopted: prism/cylinder, prism with sloped edges/cut-off cone and stepped footing. For the rectangular base shape foundation, the planar dimensions of that base were adopted as 2.50 × 2.50 m, whereas for the circular shape 2.50 m diameter was chosen. Height of each foundation was assumed as 1.40 m – maximum ground frost depth value in Poland on the basis of Polish national standard [3]. In the prism/cylinder shape footing, the base was extruded by 1.40 m in the Z-axis direction. Prism with sloped edges had it base extruded vertically by 0.60 m, then extruded by 0.80 m and inclined inwards by 45 degrees to the centre axis. In the cut-off cone, base had been extruded by 0.30 m, and then extruded by 1.10 m with 40 degrees of inwards incline angle directed to the centre axis of revolution. In both cases of stepped footing, the base had been extruded vertically by 0.60 m, then for rectangular base shape foundation area of 1.00 × 1.00 m was vertically extruded by 0.80 m. Centre point of extruded area, coincided with the centre point of base. For the circular base shape footing, second step had also been extruded by 0.80 m, however the diameter of extrusion was equal 1.30 m. All mentioned spread footings with adopted dimensions were presented in Fig. 1.

In each case, the column was placed onto the top surface of foundation and longitudinal axis of column has coincided with the centre point of foundation top surface. For the rectangular base shape footings, section of square column was adopted, where height was equal 1.00 m, and dimensions of square cross-section were 0.40 x 0.40 m. For the circular pattern footing, circular column was adopted with same height 1.00 m and cross-section diameter equal 0.40 m. Connection between each spread footing and column was assumed as rigid. Owing to the fact that analyses were performed for only a part of construction (spread footing with connected 1.00 m of column) to make analyses comparable, constant static load with value of 500 kN was adopted for each considered foundation. Mentioned force was assumed as evenly distributed onto the top surface of columns. Load eccentricity was omitted; however, it will be a part of further author's analyses.

3. Numerical model

In order to perform numerical analyses SolidWorks software based on FEM was chosen. To reflect footing located onto the ground, each analysed foundation had on its whole bottom surface vertical displacement boundary condition fixed and in the centre of that surface all displacements had also been fixed to provide full model stability. It should be noted that ground weight located onto the foundation, ground friction and subsidence was neglected in the analysis. Connection between column and footing was realized as ideally rigid – all column's displacements and rotations were transferred onto the area located directly under the column. It should be noted that model was ideal, no material and dimensions imperfections were assumed.

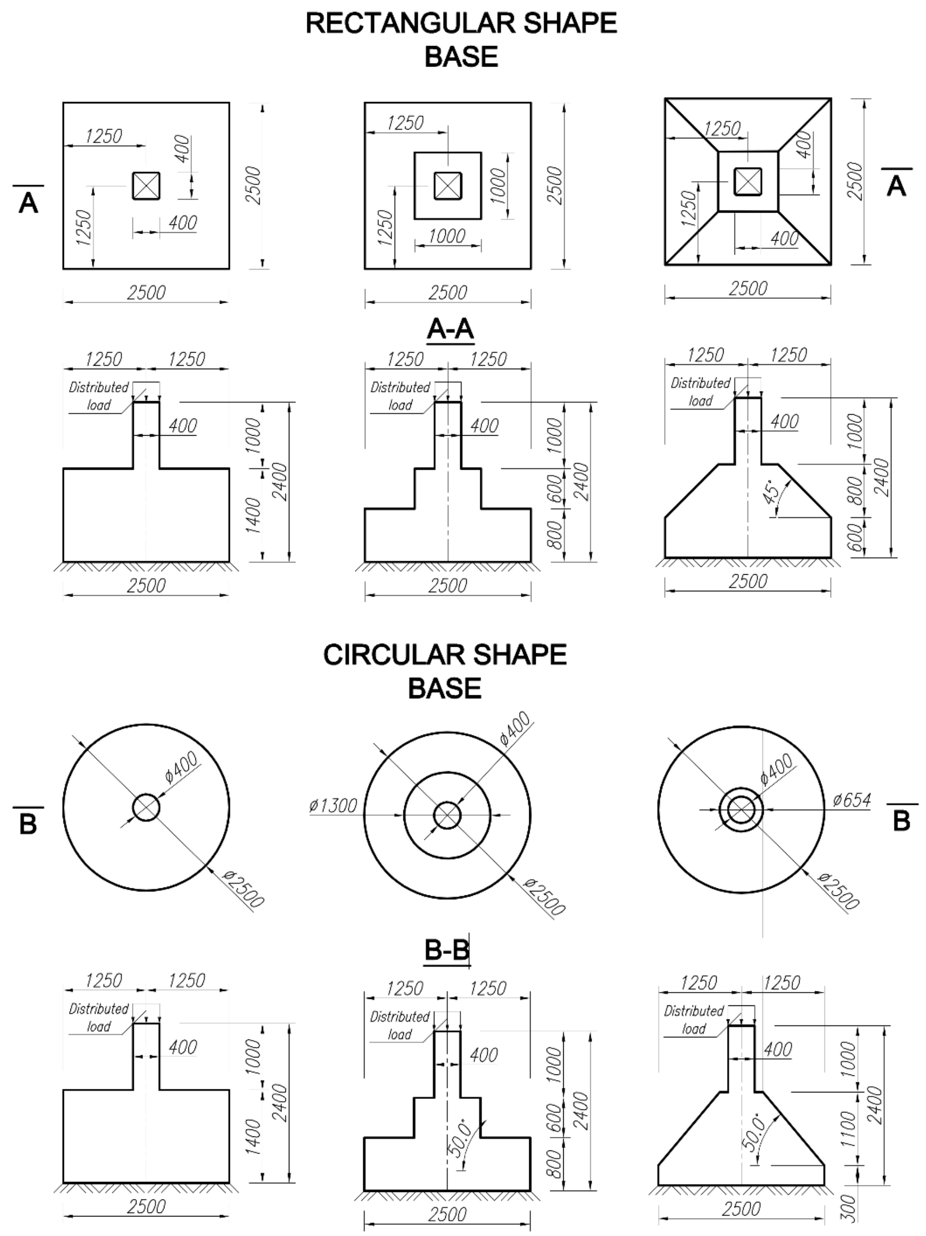

Fig. 1: Models of spread footings with rectangular/circular base shape adopted to the comparative analysis (dimensions in mm).

For each spread footing model with columns, concrete material was represented by linearly-elastic isotropic material model for which compressive strength was set to 20 MPa, which correspond to the C20/25 concrete class. Utilization of linearly-elastic isotropic material model was a result of simplification – designed spread footing dimensions were incomparably greater than dimensions of a single aggregate in concrete. It should be noted that in this paper stress results concerning only concrete material had been the subject of interest, therefore reinforced steel has been omitted in the analyses.

Discretization of both, spread footing and column was performed with 3D-Solid, 4-node tetrahedron finite elements. Maximum size of element was assumed as 50 mm, whereas in the area of column and spread footing connection finite element size was decreased to 10 mm.

Bonded contact was assumed in the connection between elements. In spite of circular base footings, additional option – mesh depending on curvature was applied.

4. Comparative analysis

The comparative analysis of stress distribution in spread footings was made for three different cases. In the first case Von Mises stresses was measured as the maximum value from the bottom surface of spread footing. In the second case Von Mises stress was read-out as the maximum value from the perimeter of column located at the connection between column and foundation. In the third case, comparison concerns shape of foundation stress plots, where minimum value of stress was limited to 0.30 MPa. Numerical results of maximum Von Mises stress obtained under the bottom surface of spread footing were presented in Fig. 2.

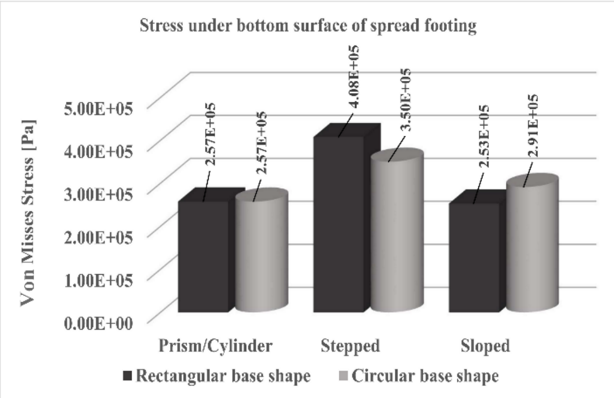

Fig. 2: Maximum Von Mises stress under the analysed foundations bases for different spread footing shapes.

As shown in the Fig. 2, stresses under each spread footing are quite low due to the assumed dimensions of spread footing. Maximum stress values depending on footing shape fit in range of 0.257 up to 0.408 MPa. The highest values of stress were obtained in the stepped footings, which was the result of axial force transfer from column. In the rectangular base shape stepped foundation the axial force from the column has been transferred onto the first step, which had 1.00 x 1.00 m area and height equal 0.80 m. According to that, on the lower step, knowing that force is approximately distributed with outwards constant angle 45° the area on which the force was distributed was the lowest, thus the highest Von Mises stress was obtained. It is worth noting that in stepped footing some part of considered foundation may not be used in transferring forces onto the ground, therefore shape and dimensions of such foundation should be optimized.

The most appropriate foundation on the basis of stress results under the footing (see Fig. 2) seemed prism and cylinder – in both obtained value of stress under the footing was nearly the same. It proved that in the volume of analysed foundation, stress was freely distributed outwardly from the column up to the bottom surface of foundation resulting in the largest area of compressive force distribution. Despite that, from the economical point of view, prism/cylinder foundation requires the highest amount of material. Weight of each spread footing foundation was presented in Fig. 3.

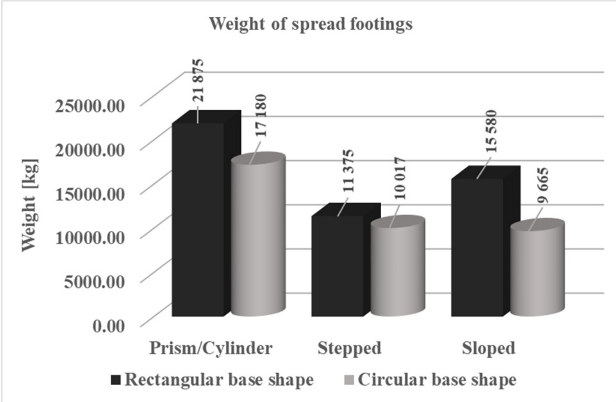

Fig. 3: Required concrete mix material weight for each presented spread footing shape.

On the basis of Fig. 3, it is clearly visible that the prism/cylinder spread footing for which the lowest stresses under the base were obtained were almost twice heavier than both rectangular/circular based stepped foundations, and from the sloped cut-off cone. The difference between the prism and the rectangular based sloped shape foundation was also high, the prism was around one and a half times heavier. Weight of concrete indirectly determines costs of each foundation. On the total cost consists also the difficulty of spread footing shape creation. According to that, stepped foundation would be the cheapest, however if lower stresses under the base are required, then the sloped foundation should be utilized. Moreover, utilization of circular shape foundations allows to additional weight reduction in comparison to the rectangular based foundations and what's more corner stresses may be considerably lowered. Of course in the stepped type of foundation it is hard to omit corner stresses occurring on the connection between steps. The only way to lower such stresses could be cast of a triangular concrete layer at the whole connection length between steps – however it requires additional labour. On the basis of presented results in Fig. 2 and foundations weight in Fig. 3 one can state that the circular based cut-off cone foundation would be the best choice.

In order to correctly design the foundation also the stresses in the column near the connection with foundations should be checked. According to [2] also punching of foundation due to column transferred force have to be check. In all cases punching requirement was easily met due to only axial force acting in analysed systems and relatively high foundation height dimension. Maximum Von Mises stresses at the connection of column with each foundation were presented in Fig. 4. It should be noted that for the results read-out, volume consisting of full column area and 10 cm of column height measuring from the top spread footing surface was taken into considerations.

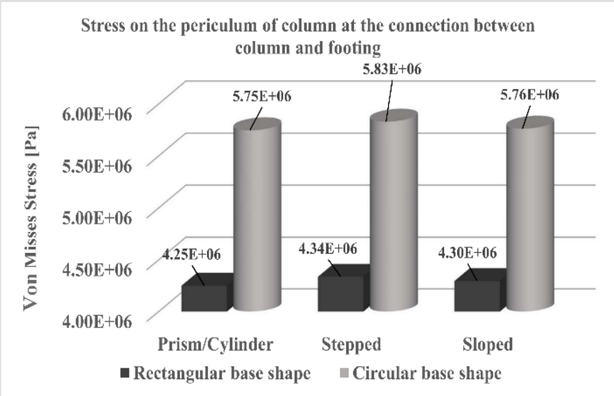

Fig. 4: Von Mises stress on the column perimeter for each analysed spread footing foundation.

On the basis of Fig. 4, the lowest and comparable Von Mises stress on the column perimeter were obtained for the columns connected with rectangular base shape foundations. Mentioned stresses were lower than for circular based spread footings in view of larger cross-section area of square column in comparison to the circular shape. Moreover, corner stresses were reduced due to introduced cornering cut-off. Each square column had its corner cut by 2 cm from each side leaving a cut with the 45° angle. Even though stresses in circular columns are higher, there is only around 1.00 up to 1.50 MPa difference. Moreover, all stresses in the column were far beyond the maximum level of 20 MPa of assumed concrete compressive strength. Despite higher values of stress, one can state that in circular columns stress distribution is far more even than in square corresponding element, however buckling direction for circular column is indeterminate. Moreover, circular columns as well as circular shape foundation requires less concrete mix.

As it was stated at the beginning of this paper, also shapes of Von Mises stress distribution were subjected into the theoretical analysis. Shapes of stress distribution for each spread footing foundation, with minimum observed Von Mises stress limited to be higher than 0.30 MPa were presented in Fig. 5.

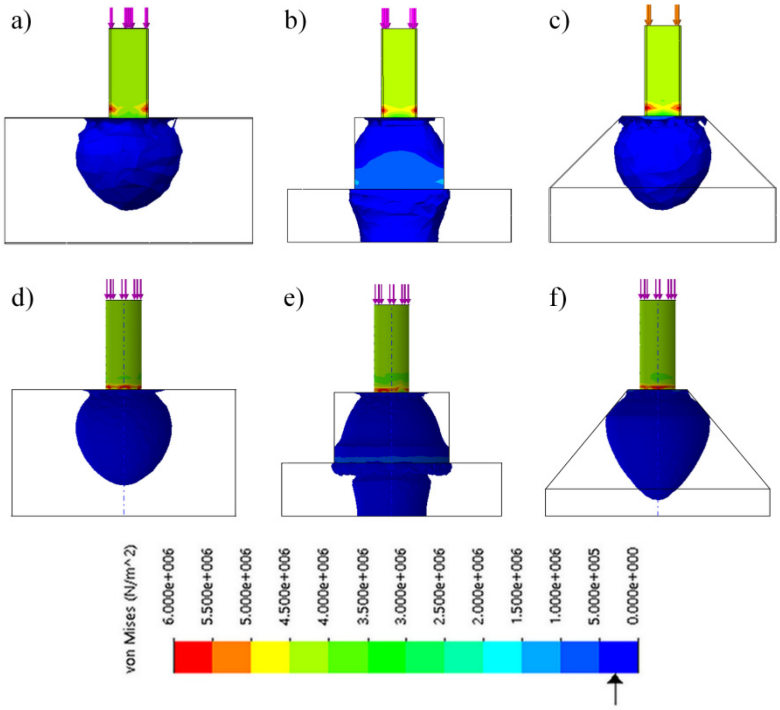

Fig. 5: Shape of Von Mises stress distribution for different shapes of spread footings. Minimum value of observed stress limited to 0.30 MPa. Spread footings: a-c) rectangular base shape, d-f) circular base shape.

Comparing Von Mises stress distribution shapes one can state that in rectangular base shape foundation for the prism (see Fig. 5a) and sloped one (see Fig. 5c), obtained results are nearly the same. According to that and discussed before material saving, the sloped one foundation would be a good choice. In the stepped type of foundation Fig. 5b and Fig. 5e, corner stresses are clearly visible. Moreover, significant amount of force is transferred onto the bottom foundation surface, due to thin first foundation step. In the circular base spread footing also cylinder (Fig. 5d) and cut-off cone (Fig. 5f) had comparable results. In the cut-off cone type of foundation slightly higher amount of force was transferred to the bottom surface of analysed foundation in comparison to the cylinder shape foundation, however force was considerably lower than in the stepped foundation. Considering the foundation weight reduction and stress distribution, sloped prism and cut-off cone would be the most appropriate foundations to be used for the pure axial compressive loading. Independently from the chosen solution – rectangular or circular base shape, blank areas in presented foundations (Fig. 5c and Fig. 5f) indicates, that further optimization should be performed.

5. Optimization

For the optimization purposes cut-off cone shape spread footing was adopted, due to considerably low Von Mises stress obtained under the foundation as well as the lowest weight. For the optimization it was assumed that the foundation diameter may change in the range of 0.50 up to 2.50 m with a 0.02 cm step. Height was assumed as constant parameter – it was assumed that the foundation is located in the fourth ground freezing depth area, for which the minimum value of height was 1.40 m. It has also been assumed that the cone slope angle may vary in the range of 40 up to 90° measuring from the horizontal line. Last two assumptions were: Von Mises stress in the column lower than 20 MPa, and stress under the foundation base lower than 1.00 MPa. Optimization was performed with the utilization of SolidWorks optimization module.

After the optimization analysis the most appropriate spread footing subjected to the pure axial loading, meeting the stated criteria had following shape: cut-off cone was reduced back to the cylinder with a 0.80 m diameter and constant height of 1.40 m. Changes in weight and also in Von Mises stresses onto the bottom surface of spread footing and on the column perimeter were presented in Fig. 6.

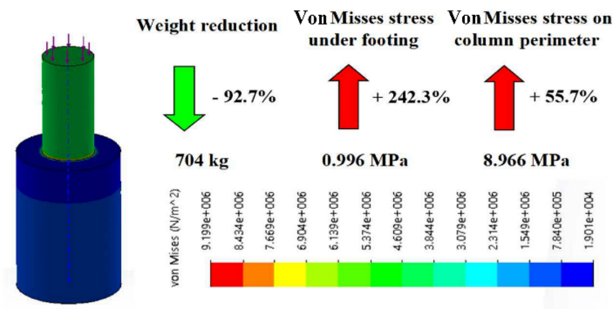

Fig. 6: Percentage difference in weight, Von Mises stress on the column perimeter and under the base footing surface for optimized foundation in comparison to the sloped cut-off cone.

Under the pure axial loading, the weight of spread footing to meet stated requirements could be significantly reduced by 92.7% in comparison to the cut-off cone weight 9665 kg (see Fig. 3), however Von Mises stress on the column perimeter and under footing have considerably increased. Despite that considering non-cohesive sand soil the load bearing capacity would be sufficient to safely transfer forces from foundation onto the ground. It is worth noting that presented analysis refers only to the pure axial loading, in practice vertical direction of compressive force is disturbed via the other loads acting on eccentricities leading to the bending momentum occurrence. According to that, depending on the bending momentum, spread footing diameter dimension should have been slightly greater to withstand rotation. In the column perimeter Von Mises stress has also increased by 55.7 % in comparison to the cut-off cone, however the value obtained was still much lower than the C20/25 concrete compressive strength. According to that one can state that the optimized spread footing through the meeting assumed analysis requirements could be safely utilized for pure axial loading.

6. Conclusion

In this paper comparative numerical analysis of stress distribution in different shapes of spread footing subjected to the pure axial loading was conducted. From six different analysed shapes of foundations it was stated that the most appropriate one would be cut-off cone footing. It was shown that mentioned footing had the lowest weight and Von Mises stress under the bottom foundation surface was one of the lowest from analysed foundations. Also presented shapes of stress distribution for each spread footing proved that forces distribution in cut-off cone footing was visually comparable with the cylindrical one. In the stepped footings corner stresses were obtained at the connection between footings steps. Moreover, values of Von Mises stress under the mentioned stepped footings bases were the highest from all analysed foundations, which was connected with the lowest area on which the axial force was distributed from the first footing step.

Through the analysis of stress distribution in the cut-off cone spread footing, where minimum stress value was limited to 0.30 MPa it was clearly visible that some part of foundation was not utilized in transferring forces. According to that small optimization was performed, where diameter and incline angles of foundation were treated as variable. Height of foundation was treated as constant value, due to assumption of fourth ground freezing depth area according to [3]. On the basis of performed numerical optimization with the utilization of SolidWorks software, cut-off cone spread footing was reduced to the cylindrical shape footing. Weight of such spread footing was reduced by over 90% in refer to the firstly analysed cut-off cone, however Von Mises stress under the footing and in the column had increased. Despite that, stresses under the footing met the assumed condition of being lower than 1.0 MPa, and compressive stress had in the column and foundation did not exceeded assumed value of concrete compressive strength which was assumed as 20 MPa – utilized C20/25 concrete class. In the next paper, authors will consider the influence of load eccentricity and the influence of translation of longitudinal column axis onto obtained shapes and values of stresses in different shapes of spread footing foundations.

This paper arisen due to lack number of papers concerning optimization of spread footing shape in order to have intended distribution of forces. It should be noted that Finite Element Method based software are powerful tools allowing to perform analyses in almost all areas of life – static analyses, dynamic analyses, electromechanical, fluid flows etc. Each of mentioned analyses can be performed with a single software. For example, dynamic analyses of mechanical wave damping in concrete blocks with injected rubber pads as well as thermal analyses using FEM software were also the present authors subject of interest and were presented in [18-20]. For the stress analysis of the elements it is possible to use many commercial software systems, based on the finite element method – FEM [21], [22]. With help of FEM software one can state that engineers can prepare much better solutions than the older one, however it should be remembered that each designed with FEM product should be professionally tested with laboratory tests or on scaled models [23].

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